Nonlinear Time Domain Modeling and Simulation of Surface and Embedded NPPS

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with contributions from

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Outline

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Motivation

- Improving seismic design (safety and economy) for Nuclear Facilities (NFs)
- **E**arthquake **S**oil **S**tructure **I**nteraction (**ESSI**) in time and space, plays a major role in successes and failures
- Accurate following and directing (!) the flow of seismic energy in ESSI system to optimize ESSI system for
  - Safety and
  - Economy
- Development of high fidelity numerical modeling and simulation tools to analyze realistic ESSI behavior, Real ESSI Simulator

Predictive Capabilities

- **Verification** provides evidence that the model is solved correctly. Mathematics issue.
- **Validation** provides evidence that the correct model is solved. Physics issue.
- **Prediction**: use of computational model to foretell the state of a physical system under consideration under conditions for which the computational model has not been validated.
- **Real ESSI Simulator**: a software, hardware and documentation system for high fidelity, high performance, time domain, nonlinear, 3D, finite element modeling and simulation of earthquake-soil/rock-structure interaction of Nuclear Facilities (NFs)

Seismic Energy Input and Dissipation for NFs

- Seismic waves input (flux) into SSI system
- Mechanical dissipation outside of SSI domain:
  - reflected (surface, NF) wave radiation
  - SSI (NF) system oscillation radiation
- Mechanical dissipation/conversion inside SSI domain:
  - plasticity of soil and rock
  - nonlinear contact zone (foundation – soil/rock)
  - plasticity/damage of structure, foundation
  - viscous coupling of porous solid with pore fluid (soil)
  - viscous coupling of structure/foundation with fluids
- Numerical energy dissipation/production

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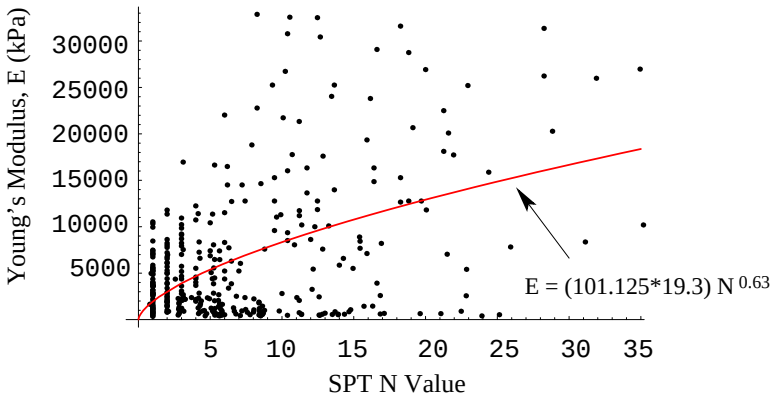
Modeling Uncertainty

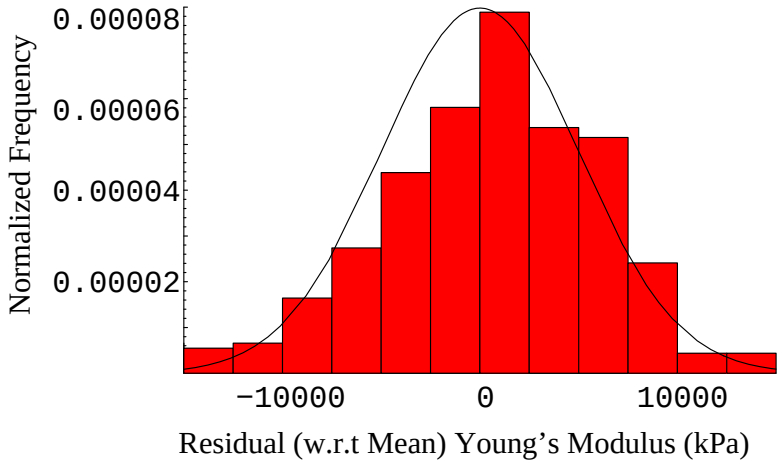
- Real ESSI goal: reduction of modeling uncertainty
- Simplified modeling: important features are neglected (structure complexity, 6D ground motions, non-linearities)
- Modeling Uncertainty: unnecessary and unrealistic modeling simplifications
- Modeling simplifications are justifiable if one or two level higher sophistication model shows that features being simplified out are not important

Complexity and Uncertainty in Motions and Material

- 6D (3 translations (horizontal and vertical), 3 rotations)
- Sources of uncertainties in ground motions (Source, Path (rock), soil (rock))
- Most engineering materials and components experience inelastic deformations for service and hazard loads
- Pressure sensitive materials (soil, rock, concrete, &c.) have complex constitutive response, tying together nonlinear stress-strain with volume response
- In addition, man-made and natural materials are spatially variable and their material modeling parameters are uncertain

SPT Based Determination of Young's Modulus





Transformation of SPT *N*-value $\rightarrow$ 1-D Young's modulus, *E* (cf. Phoon and Kulhawy (1999B))
Histogram of the residual (w.r.t the deterministic transformation equation) Young's modulus, along with fitted probability density function

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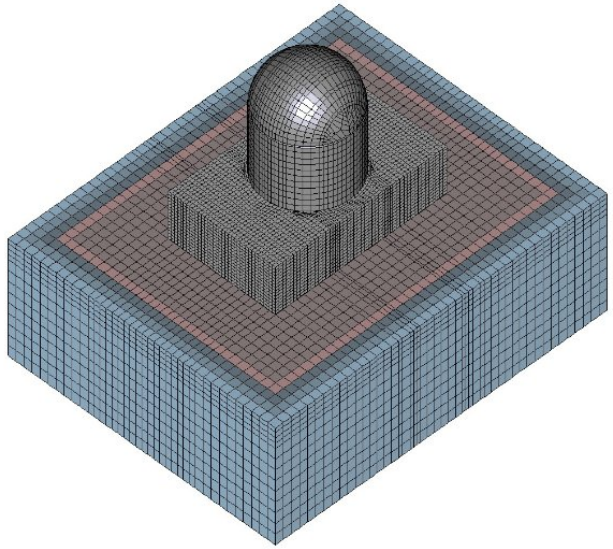
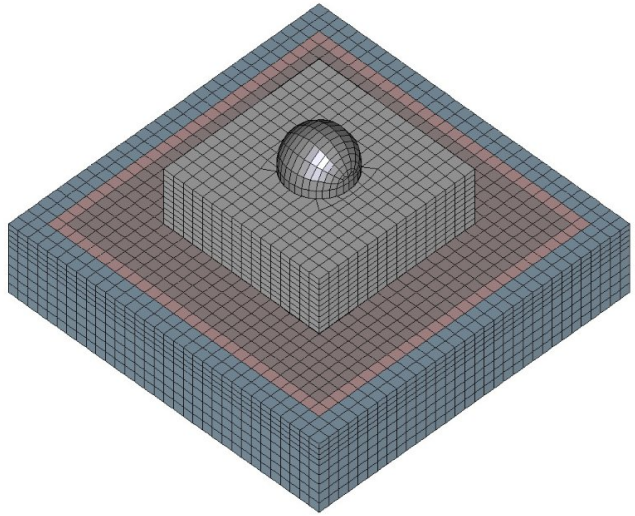
Important Issues for ESSI Modeling and Simulation

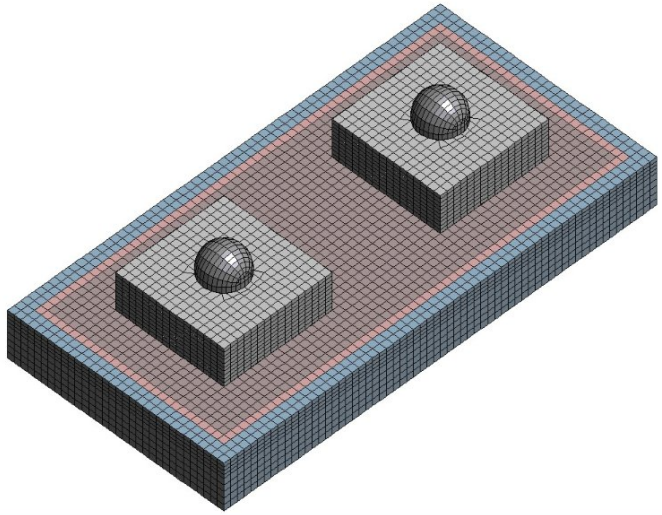
- Verification and Validation
- 6D, inclined, body and surface seismic waves
- Uncorrelated (incoherent) motions
- Nonlinear material (soil, rock, concrete, steel, &c.)
- Nonlinear foundation-soil/rock contact (dry and saturated), slip – gap
- Saturated dense vs loose soil with buoyant forces
- Isolators, dissipators

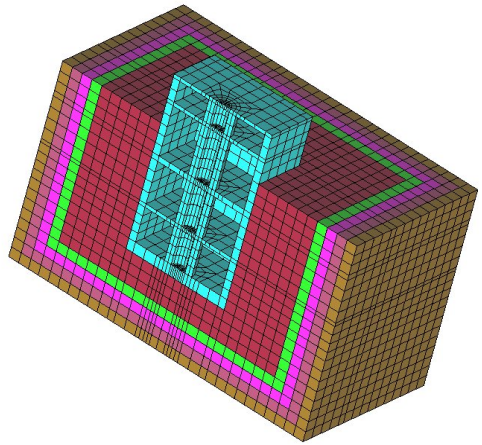
ESSI Models

Detailed high fidelity models taking into account all of the issues

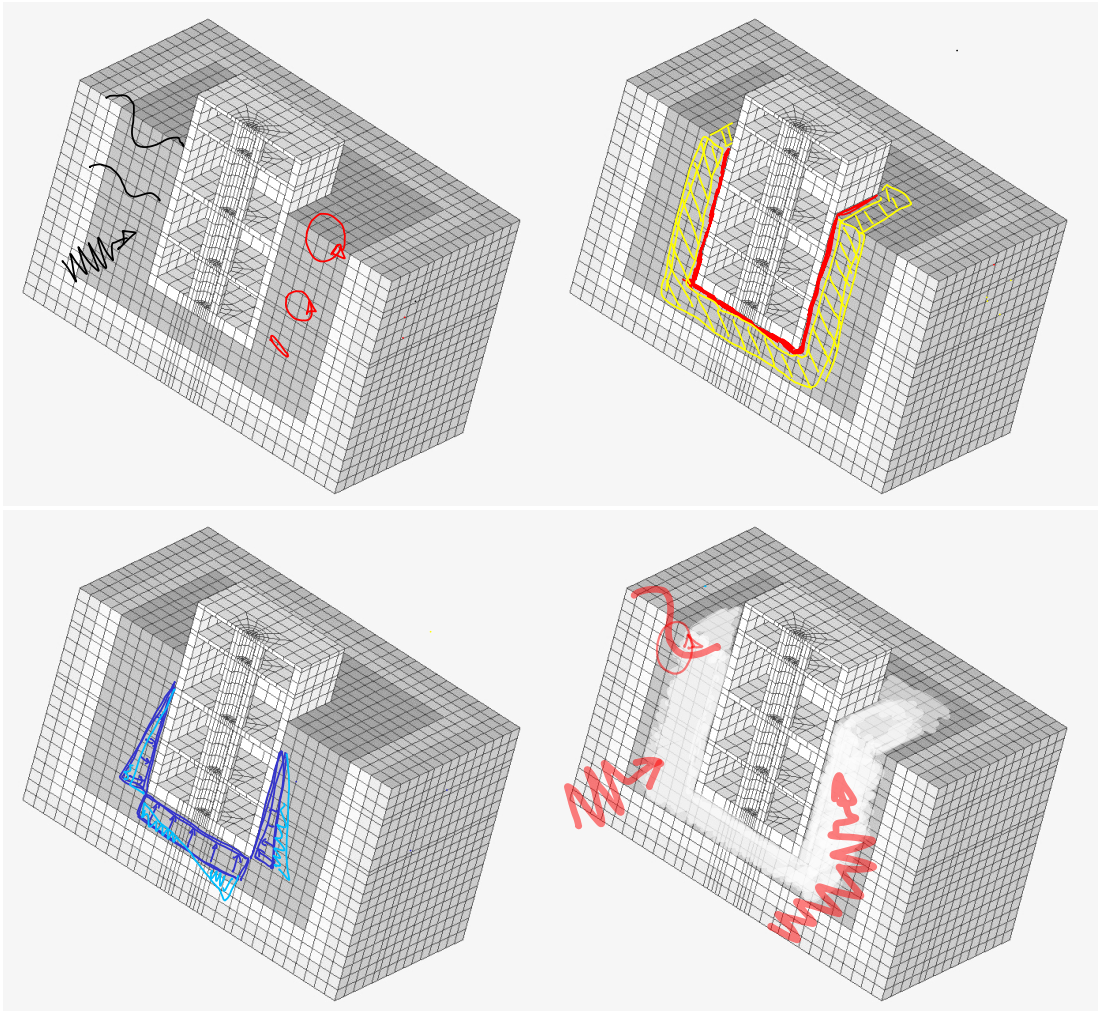








In Detail: Main ESSI Issues for SMRs



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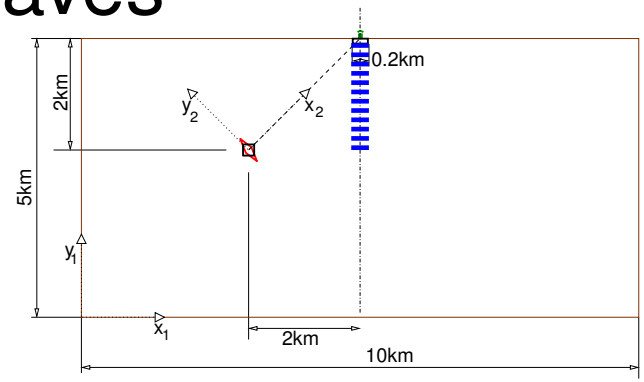
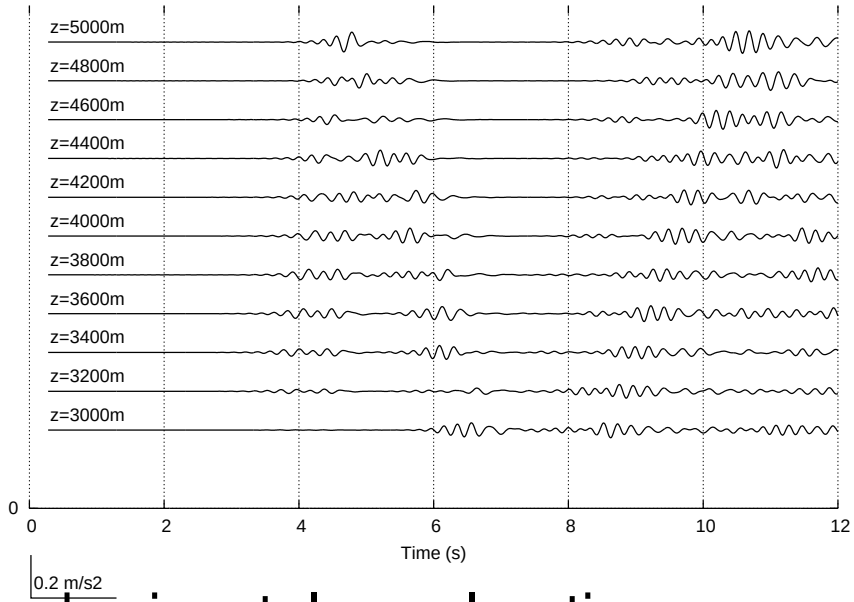
Real Earthquake Ground Motions

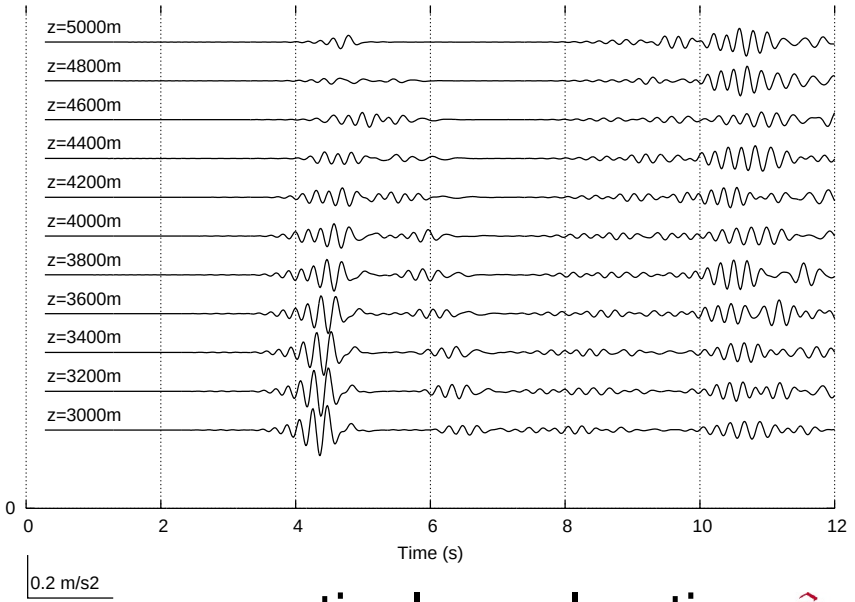
- Body waves: P and S waves
- Inclined waves
- Surface waves: Rayleigh, Love waves, &c.
- 6D waves (3 translations, 3 rotations)
- Surface waves carry most seismic energy
- Lack of correlation (incoherence)

3D, Body and Surface Seismic Waves





horizontal accelerations



vertical accelerations

Body and Surface Wave Animations

- Homogeneous soil/rock, 45^{deg} off vertical
- Homogeneous soil/rock, 45^{deg} off vertical, motion vectors
- Homogeneous soil/rock, 45^{deg} off vertical, motion vectors, NPP location

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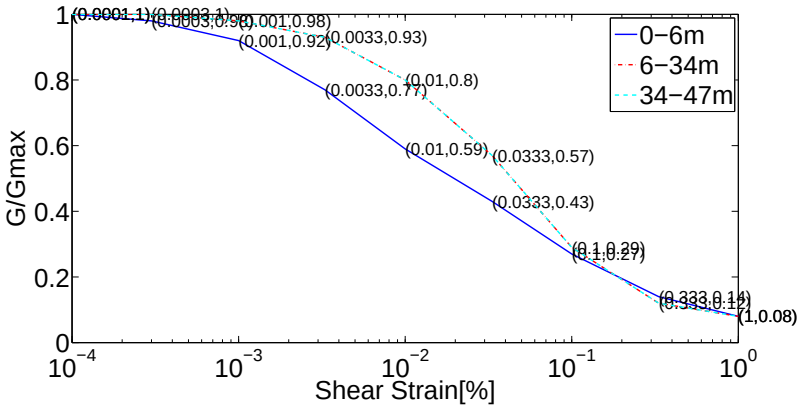
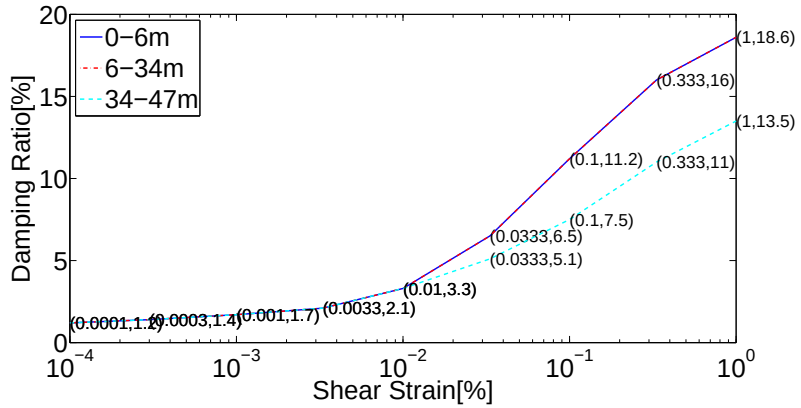
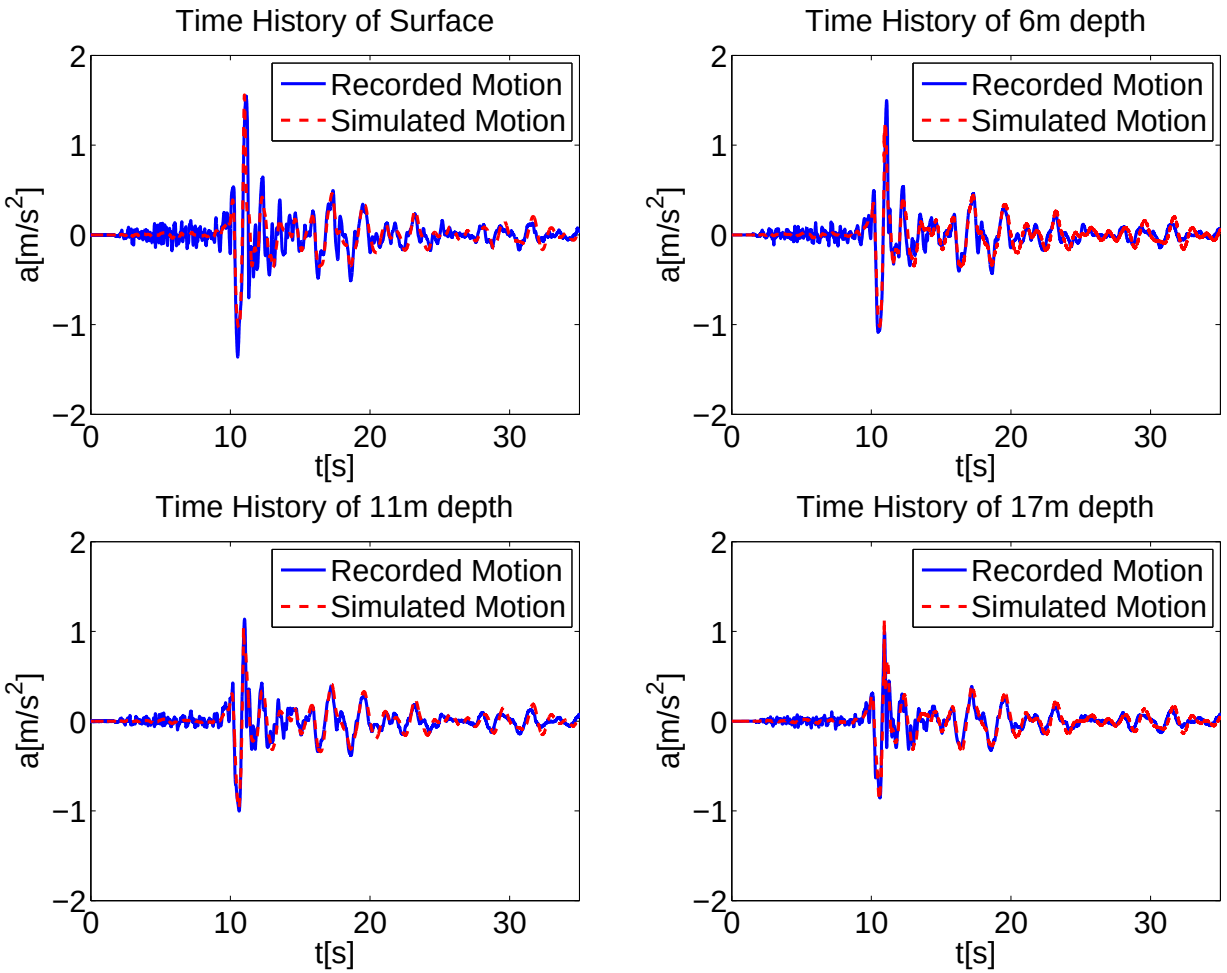
Validation: Lotung, LSST07, G/G_{max} and Damping

- Nonlinear, 3D elastic-plastic, Pisanò material model for Lotung (validation)
- 1D wave propagation, only LSST07 is close to 1D!
- No volume change data (a serious issue!)

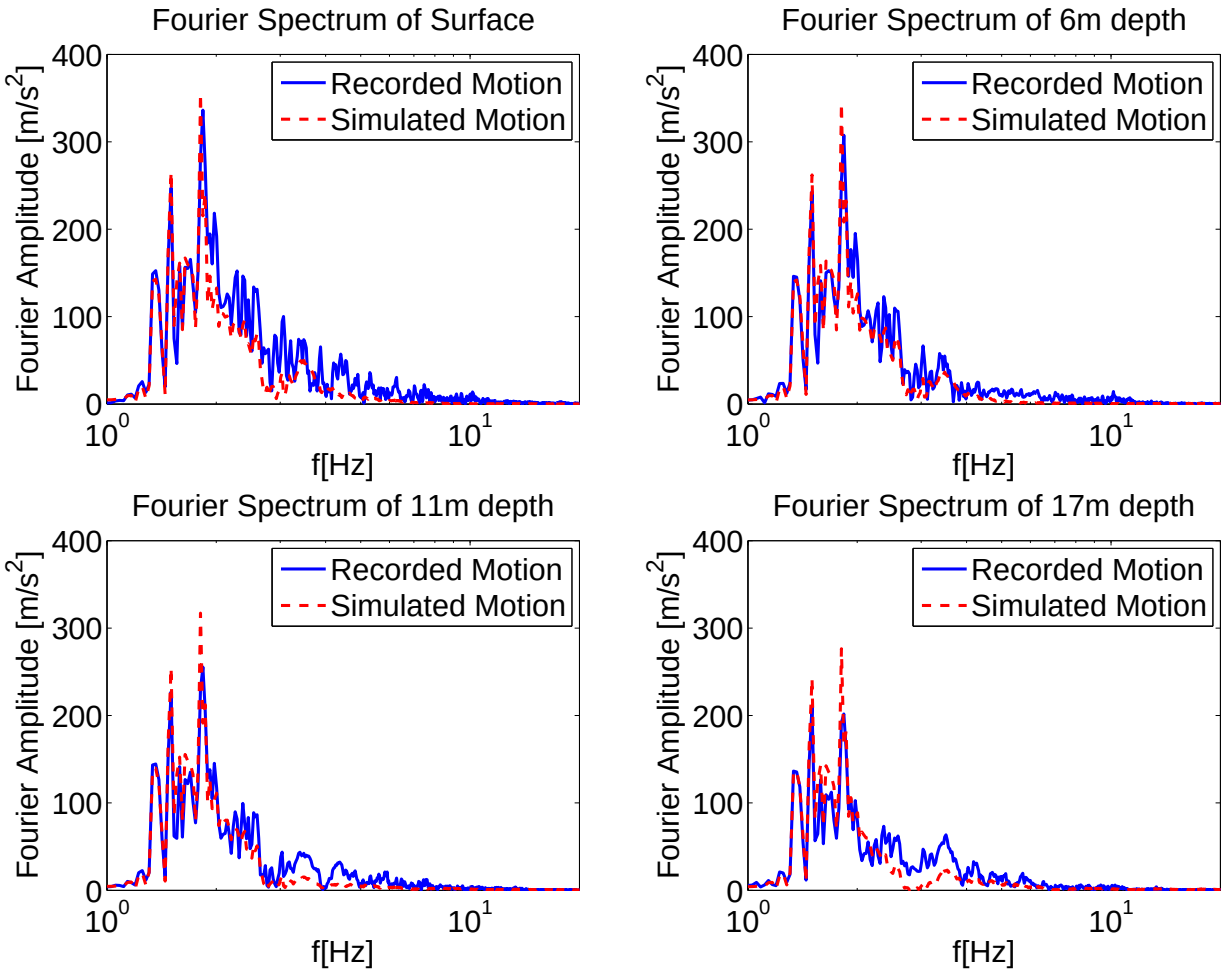




Validation: Lotung, LSST07, Downhole Motions

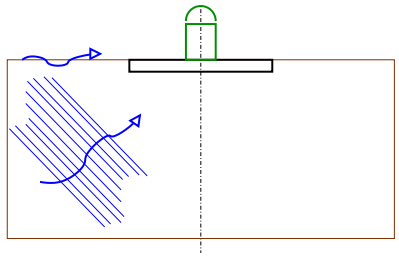


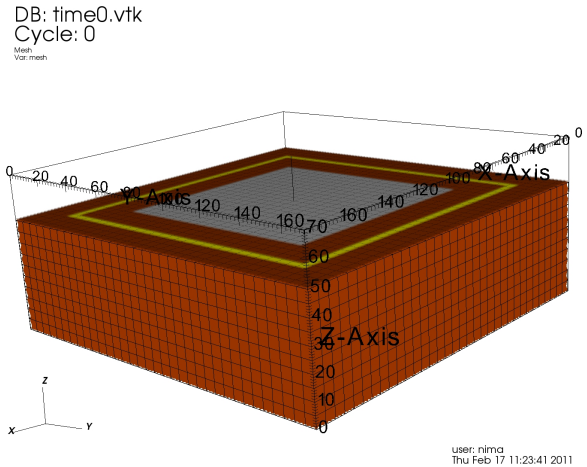
Validation: Lotung, LSST07, Fourier Spectra

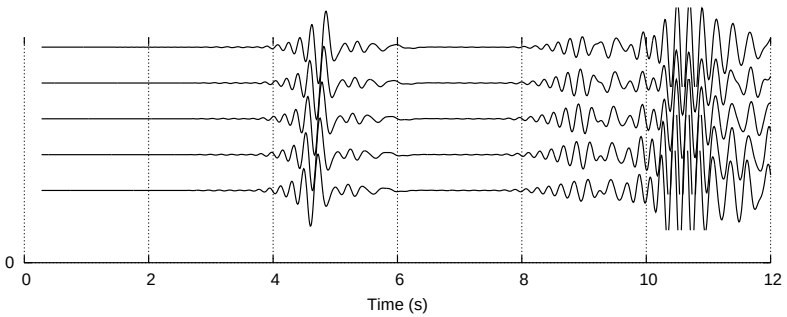


NPP with Base Slip and Gap

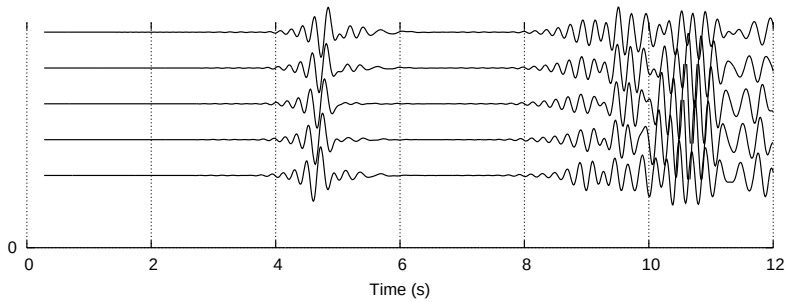
- Low friction zone between concrete foundation and soil/rock
- Inclined, 3D, body and surface, seismic wave field (wavelets: Ricker, Ormsby; real seismic, &c.)





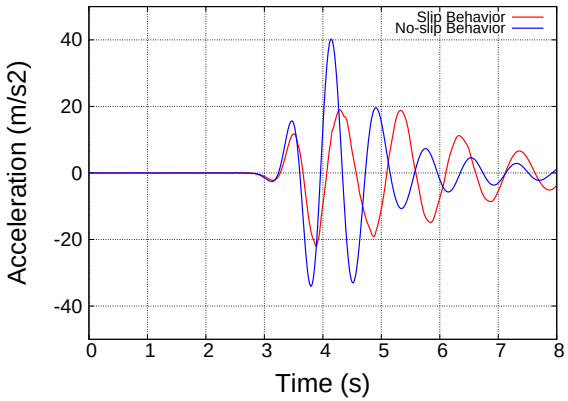


horizontal

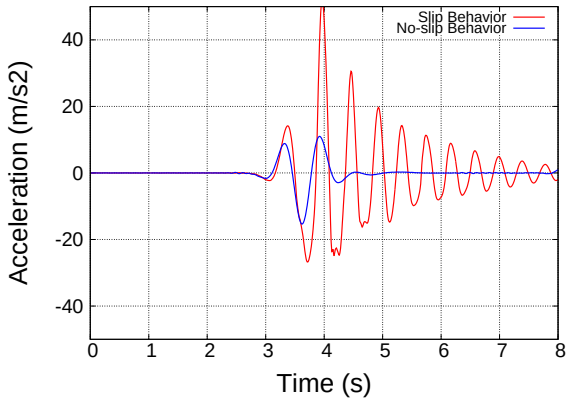


vertical

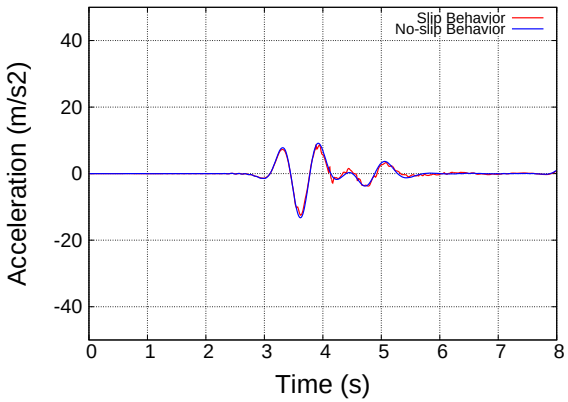
Acc. Response for a Full 3D (at 45°) Ricker Wavelet



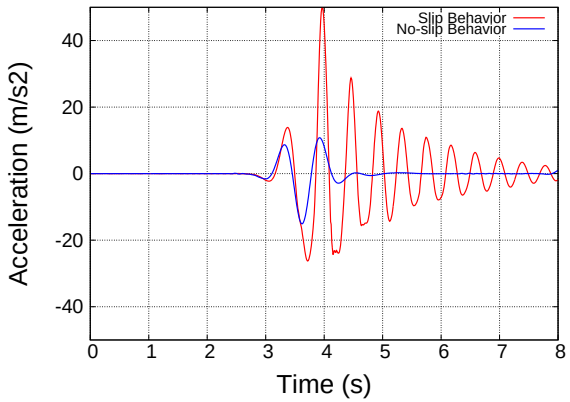
top X



top Z

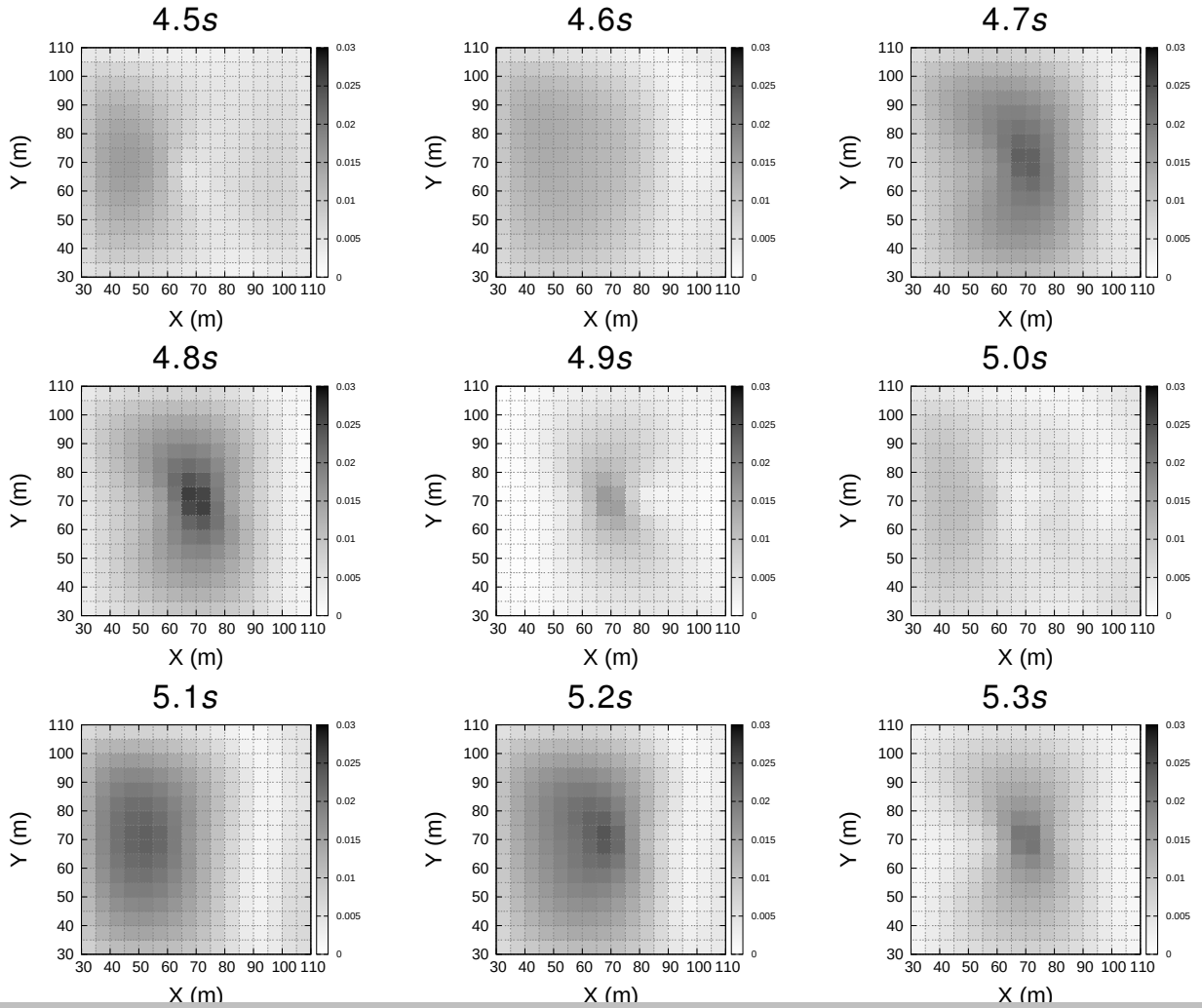


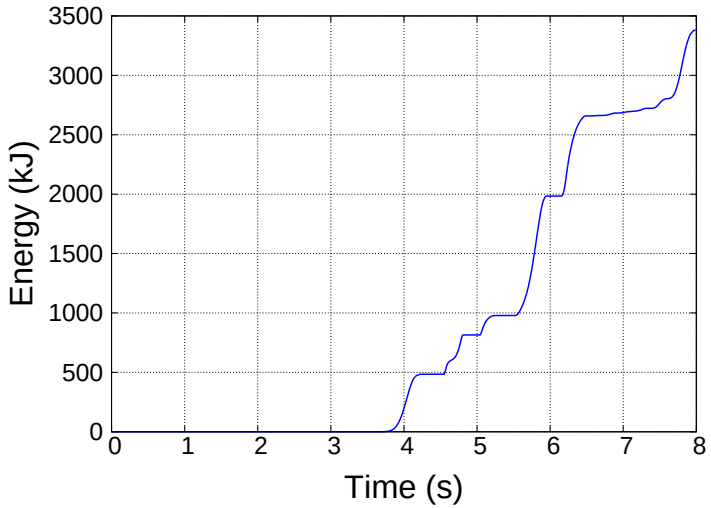
bottom X



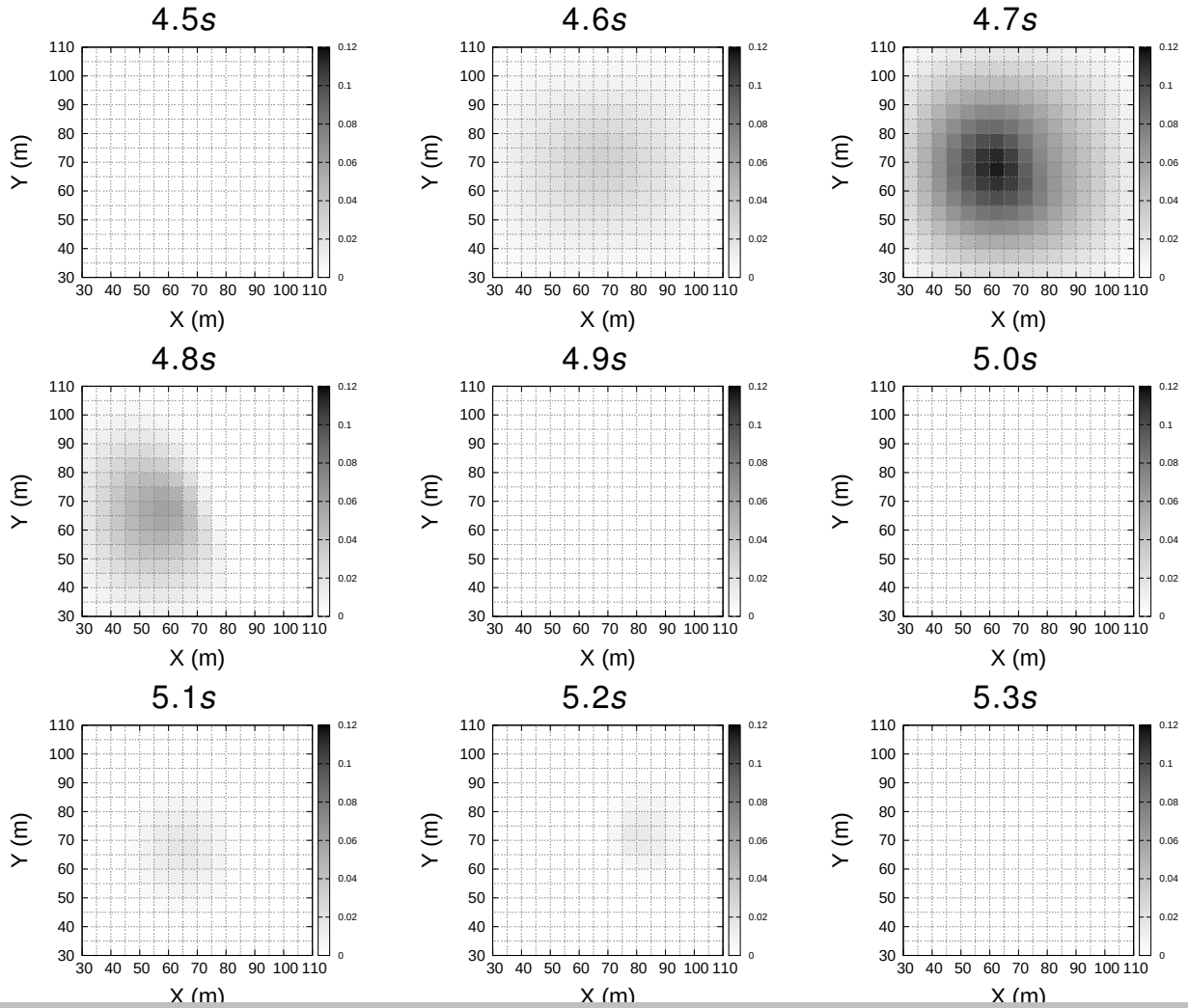
bottom Z

Slipping Response and Energy Dissipated (45° Ricker)





Gaping Response (45° Ricker Wavelet)



Summary

- Earthquake Soil Structure Interaction, in time domain, nonlinear, uncertain, plays a decisive role in seismic performance of Nuclear Facilities
- Improve design and retrofits (safety and economy) through high fidelity, physics based modeling and simulation
- Real ESSI Simulator System, verified (extensive) and validated (not so extensive), for modeling and simulations used for design, retrofits and regulatory decision making
- Education and training of users (designers, regulators, owners) proves essential

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